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SUPERCONDUCTIVITY AND CRYOGENICS FOR THE LARGE HADRON COLLIDER

Ph. Lebrun

Abstract

Key technologies to the Large Hadron Collider (LHC), the 26.7 km circumference high-energy, high-luminosity particle collider under construction at CERN, are high-field superconducting magnets and superfluid helium cryogenics. After recalling the main challenges of the project, we present the rationale for applying these technologies on an unprecedented scale and briefly indicate the status of their implementation.

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Superconductivity and Cryogenics for the Large Hadron Collider

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Key technologies to the Large Hadron Collider (LHC), the 26.7 km circumference high-energy, high-luminosity particle collider under construction at CERN, are high-field superconducting magnets and superfluid helium cryogenics. After recalling the main challenges of the project, we present the rationale for applying these technologies on an unprecedented scale and briefly indicate the status of their implementation.

1 INTRODUCTION

The Large Hadron Collider (LHC), presently in construction at CERN, the European Organisation for Nuclear Research near Geneva (Switzerland), will be upon its completion in 2005 and for the next twenty years, the most advanced research tool of the world's high-energy physics community, providing access to the energy frontier above 1 TeV per elementary constituent [1]. The LHC basically consists of two interleaved synchrotrons, 26.7 km in circumference, accelerating and bringing into collision two intense counter-rotating beams of protons, at center-of-mass energy of 14 TeV and luminosity up to 10^{34} $cm^{-2}.s^{-1}$, in four experimental points equipped with large particle detectors (Figure 1). The main parameters of the LHC as proton collider are listed in Table 1. Besides protons, the LHC will also accelerate and collide lead ion beams with energies of up to 1150 TeV, with the aim of studying new states of matter such as the quark-gluon plasma.

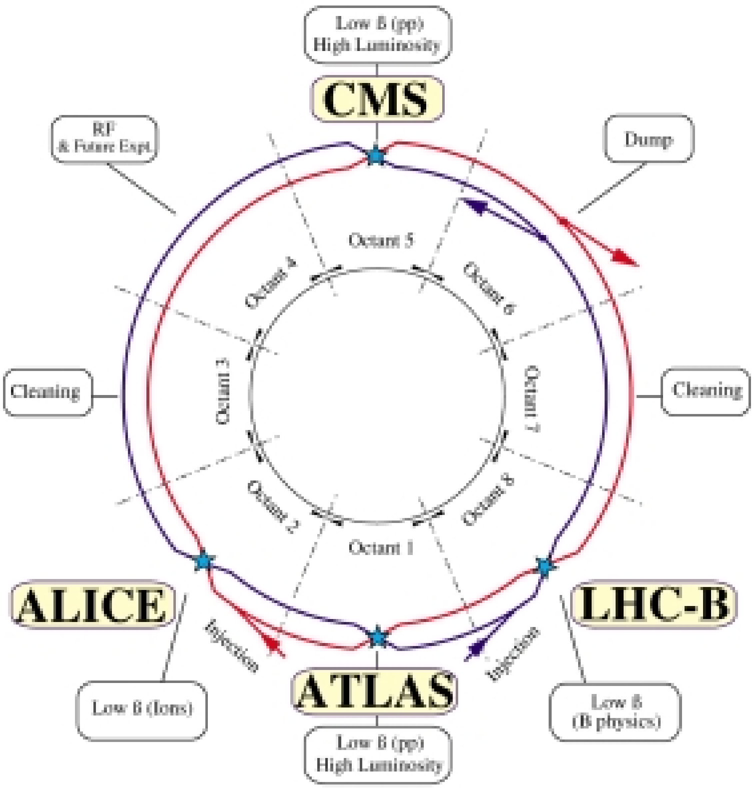

Figure 1 Overall layout of the LHC

Beam energy in collision	7	TeV
Beam energy at injection	0.45	TeV
Dipole field at 7 TeV	8.33	T
Inner diameter of SC coils	56	mm
Beam separation	194	mm
Luminosity	10^{34}	$cm^{-2}.s^{-1}$
Beam intensity	0.56	A
Bunch spacing	7.48	m
Bunch separation	24.95	ns
Bunch population	1.1×10^{11}	
Beam crossing angle	300	µrad
Luminosity lifetime	10	h
Energy loss per turn	7	keV
Critical energy of radiated photons	44.1	eV
Synchrotron power per beam	3.8	kW
Stored energy per beam	350	MJ

Table 1 Parameters of the LHC as proton collider

In order to meet these ambitious goals at an economically affordable cost, the LHC reuses the 26.7 km circumference tunnel, civil works, injector complex and infrastructure of the existing LEP collider, due to terminate its life in year 2000. The quest for high energy beams with a fixed bending radius therefore requires the intensive use of high-field superconducting magnets and consequently, a large helium cryogenic system, which constitute the key technologies of the project, described in the following. In addition, there are many other innovative aspects, both technical and organisational, which the LHC project features in view of its unprecedented size, complexity, and globality [2]; they will however not be addressed in this paper for the sake of brevity.

2 HIGH-FIELD Nb-Ti SUPERCONDUCTING MAGNETS

The drive to higher beam energy has pushed up the accelerating and guiding fields in particle accelerator devices. Together with their high electrical power consumption, which often dominates operating costs, this has led over the years to the emergence and development of superconducting technology. In fact all high-energy accelerators planned or built since the 1980s make use of superconducting acceleration cavities and/or magnets. The LHC represents the latest stage in this evolution, with its 1250 superconducting main dipoles operating at 8.33 T, 400 superconducting main quadrupoles producing gradients of 223 $T.\,m^{-1}$ [3], and several thousand other super-conducting magnets [4], for correcting multipole errors, steering the beams, and increasing luminosity in collision. All these magnets will eventually be series produced in industry.

A specific feature of the main dipoles, a cross-section of which appears in Figure 2, is their twin-aperture design. To produce the anti-parallel fields required for bending the counter-rotating beams along their paths in the tunnel, the collider needs two separate magnetic channels. This is conventionally achieved by installing side by side two separate strings of magnets, each in their own cryostat. In the LHC, two sets of windings are combined in a common mechanical and magnetic structure to constitute twin-aperture magnets, a more compact and efficient solution, as the return flux of one aperture contributes to increasing the field in the other.

The field level and quality in the magnet apertures are produced by winding high-current Rutherford-type multi-strand keystoned cables, in a graded two-layer cos θ geometry. The very large electromagnetic forces acting on the conductors are reacted by non-magnetic collars resting against the stiff iron yoke, contained in an all-welded shrinking cylinder which also acts as helium enclosure and pressure vessel.

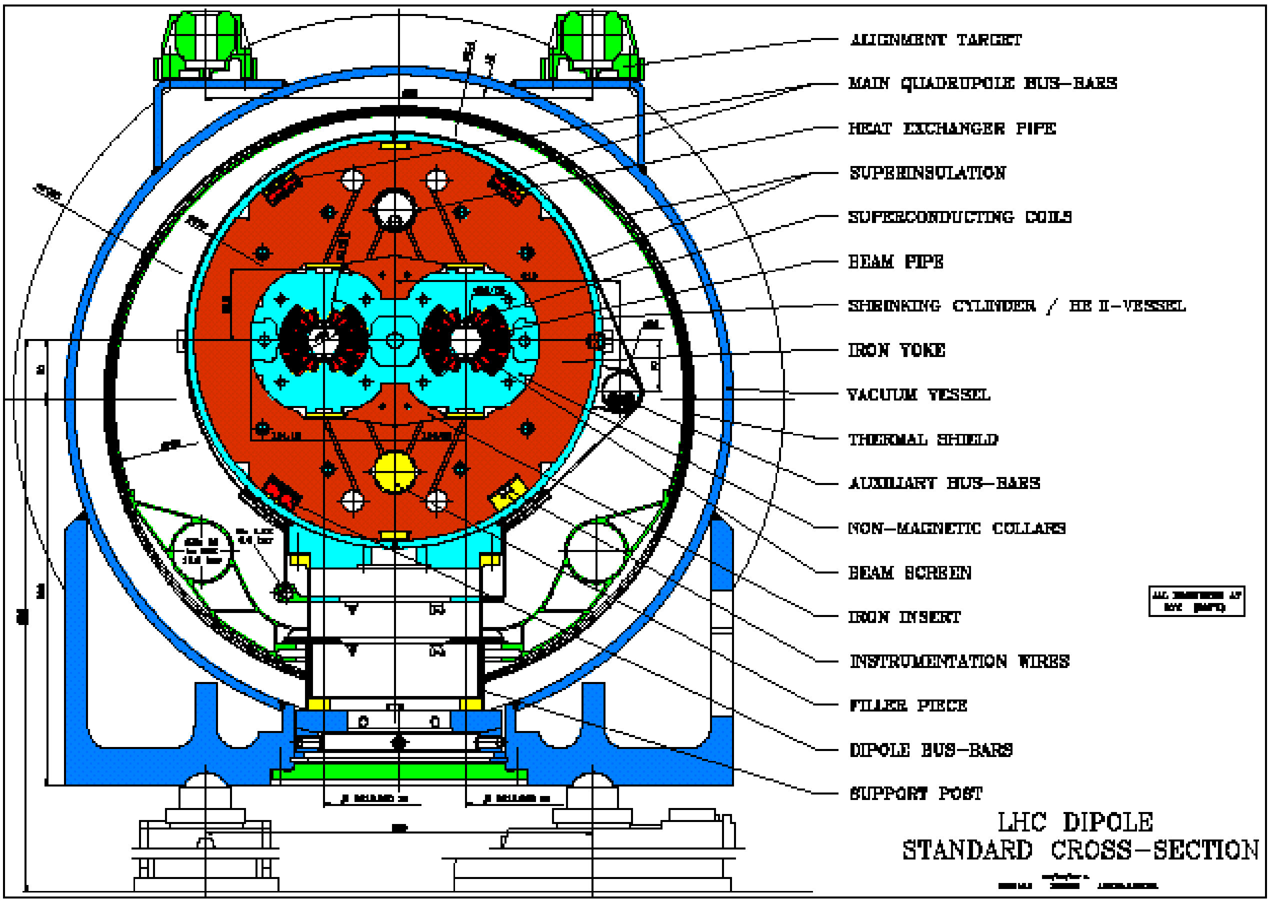

Figure 2 Transverse cross-section of LHC main dipole in its cryostat

The decreasing critical current density of Nb-Ti alloys with increasing induction (Figure 3) makes it impossible to use this material for building high-field magnets operated in normal helium at 4.5 K. The alternative A15 compounds, such as Nb_3Sn, are however plagued by their difficult implementation (wind-and-react process), limited industrial availability – the LHC requires some 1200 tonnes of superconductor – and high cost. CERN therefore decided to base the LHC project on the use of Nb-Ti operating in superfluid helium at 1.9 K, temperature at which it retains sufficient current-carrying capacity for building magnets up to about 10 T. This technique, however pioneered in the 1980s in the Tore Supra tokamak and other high-field magnets [5], is applied for the first time to the magnets of a large accelerator. The LHC magnets must preserve their field quality over a large dynamic range, matching the energy span of the proton beams from 0.45 TeV at injection up to 7 TeV in collision, and in particular at low level when persistent currents in the superconductor produces remanence. This requires the diameter of the Nb-Ti filaments in the cable strands not to exceed 7 µm, a technical/economical compromise which can be obtained by single-stack billet manufacturing.

Following a decade of development and model work, final prototype magnets built in industry have permitted to validate technical design choices and manufacturing techniques, thus leading the way for the adjudication of pre-series and series contracts for the dipoles, quadrupoles and correctors, the production of which is expected to spread over the next four years.

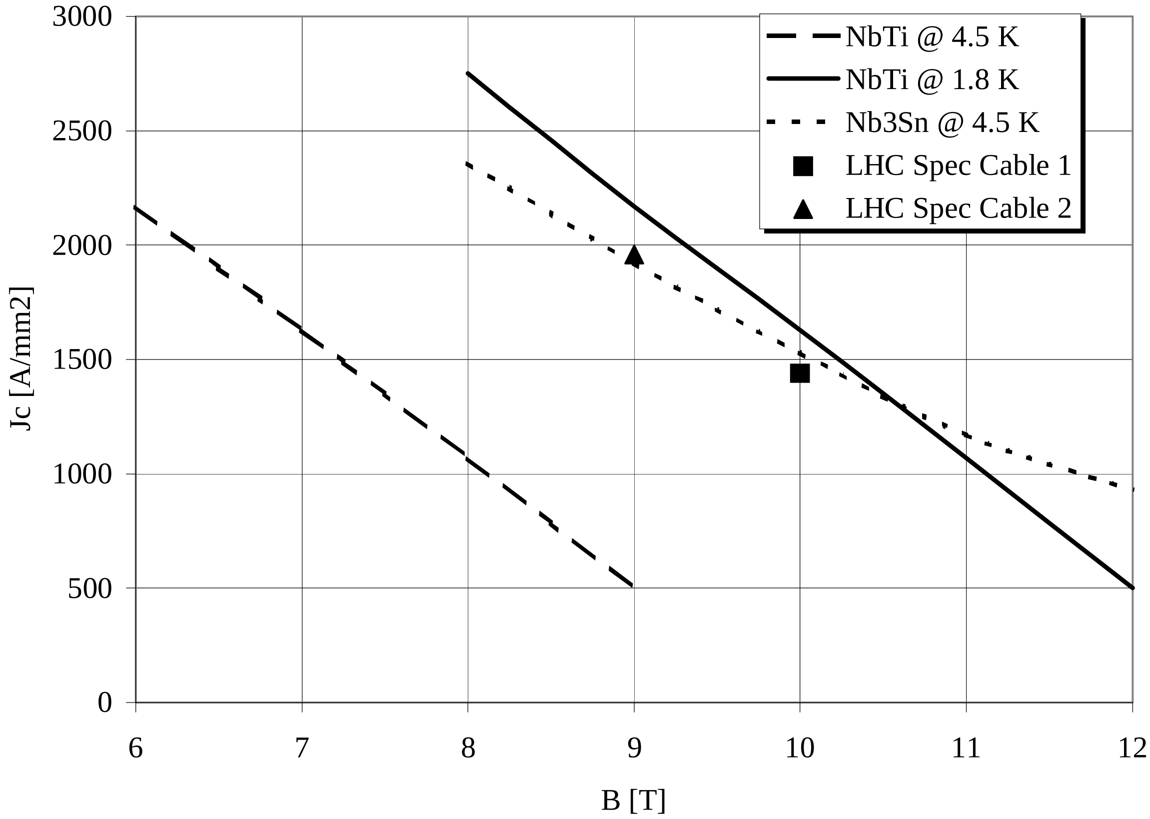

Figure 3 Critical current density of technical superconductors, showing the LHC cable specifications

3 HTS-BASED CURRENT LEADS

Powering the superconducting magnet circuits in the LHC will require feeding 3.4 MA into the cryogenic environment, some 80 % of which in the form of currents of several kA, culminating with the 13 kA rating of the main dipole and quadrupole circuits. Using resistive vapour-cooled current leads for this purpose would result in a heavy liquefaction load, exergetically equivalent to the production of an additional LHC sector refrigerator. The advent of quasi-industrial HTS materials, combined with the favourable cooling conditions provided by the availability of 20 K gaseous helium in the LHC cryogenic system, renders the use of HTS-based current leads very attractive. With a comfortable temperature difference to extract the heat from the resistive section in a compact heat exchanger, this allows to operate the upper end of the HTS section below 50 K, a temperature at which the presently available materials, e.g. BSCCO 2223 in a silver matrix, exhibit much higher critical current density than at the usual 80 K provided by liquid nitrogen cooling. The thermodynamic rationale for using such HTS-based current leads is presented in Table 2, in comparison with conventional resistive vapour-cooled leads. While the heat reaching the lower end of the lead in liquid helium is reduced by an order of magnitude, the total exergy consumption, taking into account the load on the 20 K gaseous helium flow, is cut by a factor of about 3.

Lead type	Resistive, vapour-cooled (4 to 300 K)	HTS (4 to 50 K) Resistive, gas cooled (50 to 300 K)
Heat into LHe	1.1 W/kA	0.1 W/kA
Total exergy consumption	430 W/kA	150 W/kA
Electrical power from grid	1430 W/kA	500 W/kA

Table 2 Performance of HTS-based current leads for the LHC, as compared to resistive vapour-cooled leads

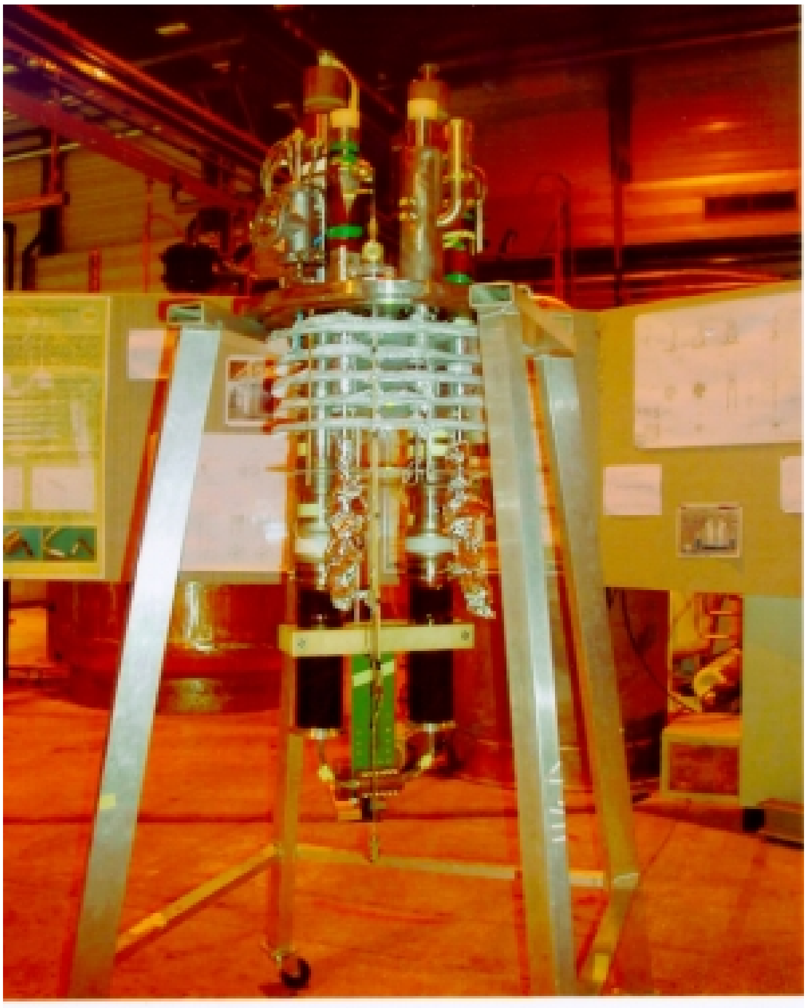

Figure 4 A pair of 13 kA prototype HTS-based current leads

After conducting tests on material samples, CERN has procured from industry and intensively tested prototypes of HTS-based current leads for 13 kA and 0.6 kA, thus enabling to demonstrate feasibility and performance of this solution, identify potential construction problems, address transient behaviour and control issues, and prepare the way for procurement of series units [6]. Figure 4 shows a pair of prototype 13 kA leads being prepared for tests in the laboratory.

4 SUPERFLUID HELIUM CRYOGENICS

The prime reason for superfluid helium cooling of the LHC magnets is the lower operating temperature, and hence the increased working range of the superconductor. However, as the specific heat of the Nb-Ti alloy – and that of its copper stabilising matrix - rapidly fall with decreasing temperature, the full benefit of the lower-temperature operation may only be reaped, in terms of stability margin, by making effective use of the particular transport properties of superfluid helium, both for extracting heat – whether steady or transient dissipation – from the magnet windings, and for transporting it over the long distances encountered in a large accelerator to the nearest heat sink [7]. The low bulk viscosity of superfluid helium enables it to permeate the magnet windings and make use of its very large specific heat - typically 2000 times that of the cable per unit volume - for buffering thermal disturbances, as well as of its huge thermal conductivity at moderate heat flux – 1000 times that of OFHC copper, peaking at 1.9 K – to transport it away. This requires the electrical insulation of the superconducting cable to preserve sufficient porosity and percolation paths while still fulfilling its demanding dielectric and mechanical functions. This has been obtained with a moderate filling factor of the keystoned cable and staggered wrappings of polyimide tape.

The large, finite thermal conductivity of superfluid helium, which was used in earlier projects to transport the heat over distances of up to a few tens of meters, is notably insufficient given the heat loads and geometric configuration of the LHC, where every 3.3-km long sector must be cooled from its dedicated refrigerator, and the thermodynamic penalty of low-temperature operation limits the overall temperature drop for heat extraction and transport to a mere 0.1 K. The LHC magnets thus operate in static baths of pressurised superfluid helium, a single-phase, quasi-isothermal medium, cooled by continuous heat exchange with flowing saturated superfluid helium, the latent heat of vapourisation of which provides a quasi-isothermal heat sink (Figure 5). This cooling scheme, which involves two-phase flow of superfluid helium in quasi-horizontal tubes, has been intensively studied on test loops and validated on a full-scale prototype magnet string.

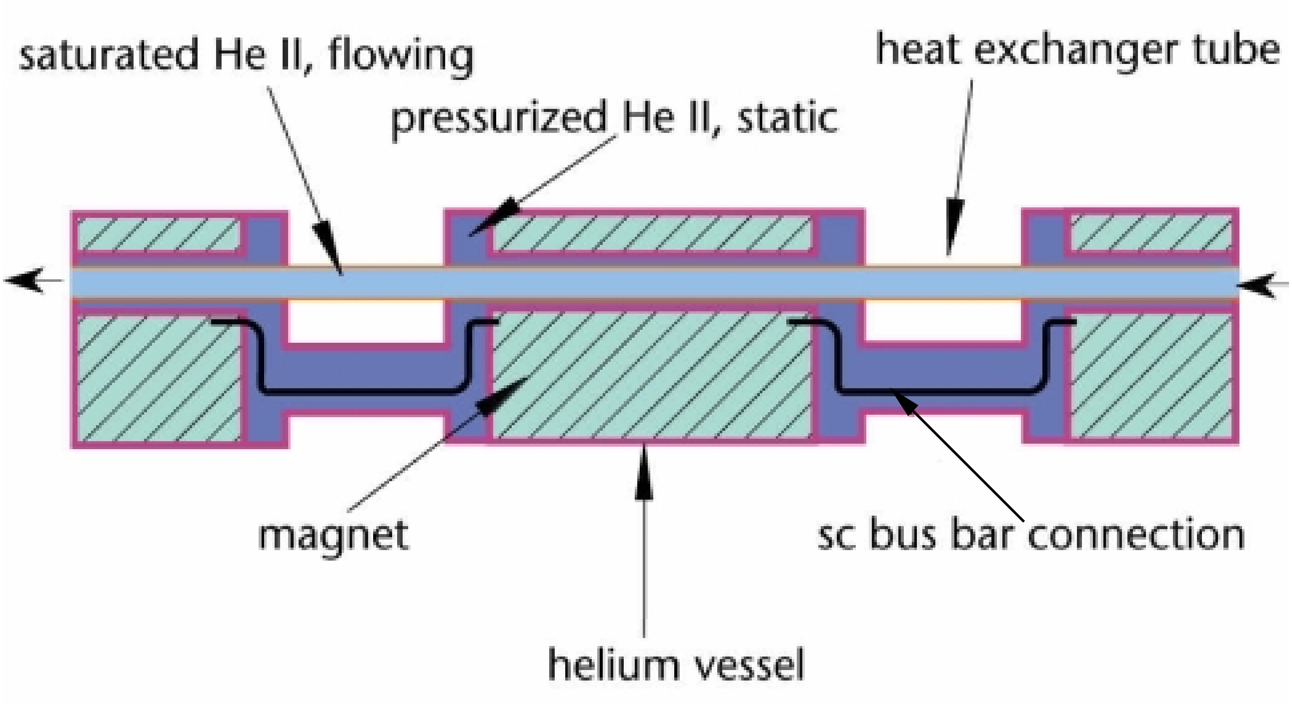

Figure 5 Principle of the LHC magnet cooling scheme

The high thermodynamic cost of refrigeration at 1.9 K requires careful management of the system heat loads. In particular, it is essential to try and intercept heat loads at the highest possible temperature, so that only residuals reach the costly 1.9 K level. This has been achieved by the combined use of intermediate shielding, multilayer insulation and conduction intercepts in the design of the cryostats (Figure 2), as well as by the installation of beam screens, cooled between 5 and 20 K by supercritical helium, for absorbing the largest fraction of the beam-induced heat loads – mostly synchrotron radiation in the UV range. Figure 6 gives an overall view of the thermodynamic states of helium in the different LHC cryogenic circuits.

In view of the low saturation pressure of helium at 1.8 K, the compression of high flow-rates of helium vapour over a pressure ratio of 80, can only be economically achieved by means of multi-stage cold hydrodynamic compressors. This technology, together with that of low-pressure heat exchangers, had to be developed specifically for this purpose, and integrated into novel thermodynamic cycles making the best possible use of the available components in order to minimise irreversibilities [8]. Following development and prototyping of the critical components, and detailed thermodynamic studies conducted in partnership with industry, eight 2400 W @ 1.8 K refrigeration units have been ordered from two companies, and will be delivered from 2001 onwards. The overall c.o.p. of these units, once connected to the conventional 4.5 K helium refrigerators, is expected to be around 900 W/W.

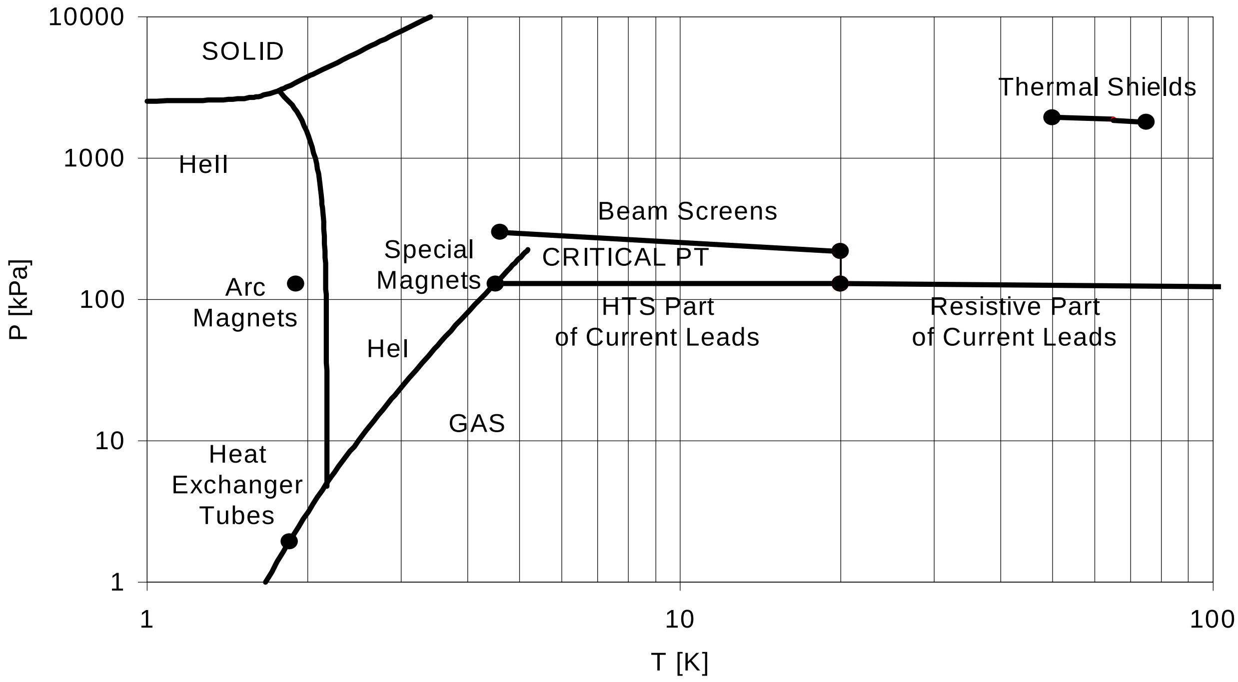

Figure 6 Thermodynamic states of helium in the LHC cryogenic system

5 CONCLUSION

After a decade of focussed R&D, the LHC construction is now in full swing. Industrial contracts have been awarded and are under execution for the procurement of some 8000 superconducting magnets and of the largest superfluid helium cryogenic system ever built. This is clearly a measure of the technical maturity of technologies which existed only in the laboratory some years ago, as well as of the role of big science as a motor of technical development.

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